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Paper 10

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Prediction of Chlorine Residuals in Streams Receiving Sewage Effluent

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Water Resources Branch

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RE: WATER RESOURCES PAPER 10 - PREDICTION OF CHLORINE RESIDUALS IN STREAMS RECEIVING SEWAGE EFFLUENT

The results presented in Water Resources Paper 10 are those of an ongoing project, developing assessment techniques for water quality prediction in effluent mixing zones in streams and rivers.

During the initial stage of this project, the applicability of readily available analytical solutions of the convective-diffusion equation was examined because of the simplicity of the solutions. Based on the results of this phase of the study, further development work is being undertaken. As such, the models described in this paper should not be construed as being final tools for the prediction of residual chlorine levels in Ontario streams.

Information on the continued progress of this study can be obtained from the River Systems Unit of the Water Resources Branch.

Don Jeffs
Supervisor
Water Modelling Section

Water Resources Paper #10

PREDICTION OF CHLORINE RESIDUALS IN STREAMS RECEIVING SEWAGE EFFLUENT

by

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River Systems

Water Modelling Section

Water Resources Branch

Ministry of the Environment

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ABSTRACT

The chlorine residuals discharged in treated sewage effluents to streams have caused concern because of their toxic effects to aquatic biota and potential health hazards through combinations with other substances to form carcinogens. The concentrations of instream chlorine residuals generally decrease with increasing distance from the outfall due to the dispersion of the effluent as well as by assimilation of the material by chemical, physical and biochemical instream processes. The report deals with the development of a methodology applicable to the prediction of total residual chlorine concentration in the mixing zones of shallow streams and rivers. Data collected in shallow streams in Southern Ontario during summer 1976 and winter 1977 have been used in the development of prediction techniques. The field surveys were primarily designed to study the magnitude and extent of decay of the residual chlorine in streams receiving sewage effluents. The decay rate coefficients of the chlorine residuals and other parameters of models derived from this data are subject to approximations. The study is mainly concerned with the development of predictive techniques and thus the contents of the report should be viewed in this perspective.

In one of the streams, the chlorine residuals were found to disappear in less than 945 m below the outfall; however, there were significant concentration variations in the transverse direction. The gross first order decay rates of the chlorine residuals in the two successive sections of the stream below the outfall were found to be 0.27 per minute and 0.082 per minute (to base 10) . The attenuation of concentration due to the dispersion effects was expressed by an apparent decay rate, assuming that the attenuation of the mean concentration of a conservative material in the plume follows a first order decay law; the apparent decay rates were found to be about 30% of the gross decay rates under survey conditions. A two dimensional mathematical model was developed for the prediction of the distribution of instream total residual chlorine concentration in the mixing zone of the stream. The model includes transport of the material by convection and decay in the longitudinal direction, as well as dispersion in the lateral direction. Some difficulties were encountered in the calibration of the model due to the limitations imposed by the available data, as well as the need to use an average value of the kinetic rate coefficient for the entire study stretch as required by the model formulation. The predictions of the model were intrepreted by taking the appropriate instream processes into consideration, thus overcoming the limitations of calibration. The model was applied to predict the spatial distribution of total residual chlorine concentration under different flow conditions. The predictions of the model show that the

residual chlorine concentration levels increase at higher flows at the lateral boundary of the mixing zone (one third width) at some downstream transects due to increased transverse spread, as well as reduced decay of the material. This is contrary to the general belief that the instream concentrations would be lower at higher flows.

Investigations in another stream indicated the persistence of the chlorine residuals for more than 4.8 km below the outfall during both summer and winter seasons. Cross-sectional variations in concentration were present in a stretch of 610 m below the outfall; however, the percentage variations were quite small. The first order decay rates were found to be 0.0052 per minute and 0.012 per minute (to base 10) for the two successive sections below the outfall during summer; whereas during winter the corresponding values were 0.0095 per minute and 0.0029 per minute (to base 10). A plug flow model was found to be adequate to describe the observed concentration distributions in this stream; the model calibration was satisfactory.

The temperature dependence of the decay rate of the residual chlorine was expressed by the well known van't Hoff-Arrhenius relationship. The theoretical value of the temperature correction factor was found to lie in the range 1.02 to 1.04 at pH and temperature values normally encountered in practices. Based on the field results, a higher range of 1.12 to 1.14 was obtained for the temperature correction factor; however, these values should be treated as tentative because of limitations of the data.

The models described in this report are applicable to shallow streams in which steady state conditions prevail. For application to natural streams in which the hydraulic and biochemical processes can vary significantly from one reach to another, it is necessary to formulate the model such that reach dependent rates can be specified; further investigations required to develop such a model are recommended. Considering the limitations, the model as presented can be applied as a useful tool to practical situations where the reach dependency of the model coefficients is not significant.

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1. INTRODUCTION

1.1 GENERAL

Chlorine is used as a disinfecting agent in wastewater treatment practice in order to destroy the microorganisms of public health concern before the effluent is discharged to a receiving body. In this regard, chlorination practice has been significantly effective in the control of the outbreak of waterborne diseases. In order to achieve a satisfactory disinfection of the wastewater effluents, it has become a common practice to specify a minimum residual concentration level in the effluent; the present Ministry of the Environment practice requires a minimum concentration of 0.5 mg/L after a contact time of 30 minutes. In recent years, however, the discharge of chlorine residuals to receiving water bodies has caused concern because of their toxic effects to aquatic biota and potential health hazards. A review of the toxicity of chlorine residuals to aquatic life and the potential carcinogenic effects attributable to the chlorine residuals, as well as areas of concern associated with conventional disinfection practices in Ontario, has been presented by Ellis (1976). This report deals with the development of assessment techniques to evaluate the impact of various management alternatives in the mixing zones of shallow streams.

The distribution of instream chlorine residual concentrations in shallow streams is governed by the combined effects of chemical reactions, mixing of effluent with the stream water and other physical and biochemical instream processes. In a portion of the cross-section of the stream below the outfall, the concentration of pollutants such as residual chlorine may be higher than the allowable limits at some locations in the stream; this segment of stream is usually termed a "mixing zone" although it may be more appropriate to call it a "zone of non-compliance". The segment of stream beyond the boundaries of this zone, wherein the water quality is favourable for aquatic life, is usually termed a "zone of passage".

The Ministry of the Environment Water Quality Criteria (1974) for the protection of fish and other aquatic life states that the discharge to receiving waters of toxic substances in concentrations or combinations that may be harmful to human, animal, and/or aquatic life, is not permitted; however, an exception is made when mixing zones in the vicinity of the outfall are permitted. According to the criteria for zones of passage and mixing, at least two thirds of the total cross-sectional area of a stream should be characterized by a water quality which is entirely favourable to the aquatic community at all times.

1.2 RESIDUAL CHLORINE FORMATION

The dissolution of chlorine in water results in the formation of hypochlorous acid ($HOCl$) and hypochlorite ion (OCl^-). The hypochlorous acid reacts with ammonia present in the wastewater resulting in the formation of monochloramine (NH_2Cl), dichloramine ($NHCl_2$) and trichloramine (NCl_3). Other chlorinated compounds

may also be formed depending upon the chemical constituents of the stream and wastewater. A more detailed review of the fundamentals of chlorination is presented by Ellis (1976) and Fair and Geyer (1961).

The portion of chlorine residual concentration present in the forms of HOCl and OCl^- is referred to as the "free residual chlorine", whereas the portion present as chloramines is termed "combined residual chlorine". The sum of free and combined forms is known as "total residual chlorine (TRC)". In chlorinated sewage effluents, the residual chlorine is present as chloramines, while free residual chlorine is seldom observed. The allowable concentration of residual chlorine for protection of aquatic life is specified in terms of total residual chlorine. Hence, the total residual chlorine parameter is used in this report.

1.3 OBJECTIVES

This investigation was undertaken to develop a methodology applicable to the assessment of various management alternatives on the TRC levels in the mixing zones of streams below sewage treatment plant (STP) outfalls and thus, aid in the application of the mixing zone criteria. The specific objectives of the study are as follows:

1. To determine the relative effects of dispersion and chemical reaction on the reduction of instream total residual chlorine (TRC) concentrations.

2. To investigate the temperature dependence of the reaction rate of chlorine residuals.

3. To develop mathematical models applicable to the prediction of spatial distribution of TRC in streams receiving sewage effluent.

4. To investigate the effects of streamflow variations on the TRC levels in the mixing zones.

II. INSTREAM RESIDUAL CHLORINE MODELLING

2.1 INSTREAM PROCESSES

2.1.1 Mixing and Dispersion

Mixing phenomenon in natural streams tends to reduce non-uniformities or gradients in composition or properties of a material in bulk and is accomplished by the movement of materials between various parts of the streamwater. The movement of the material itself occurs by a combination of bulk flow in laminar and turbulent regimes, and molecular and turbulent diffusion processes; the resultant process affecting the transport of the material is commonly known as dispersion. A review of the basic physical exchange processes in natural streams is presented by the author (1974).

The degree of mixing and dispersion in a receiving stream is dependent on the hydraulic characteristics of the outfall and of the stream channel. In the case of a shallow, uniform stream, effluent released from a bank outfall may hug the shoreline for a considerable distance. In the case of a diffused (finite width) outfall, the initial dilution and further mixing and dispersion of effluent may be dependent on the hydraulic characteristics of the diffuser. The channel hydraulic characteristics such as the cross-sectional depth and velocity distributions, presence of pools, rapids and meanders, etc., will influence the mixing and dispersion. Excessive growths of aquatic weeds and algae tend to reduce mixing. Ultimately, the cross-sectional concentration distribution attains uniformity at some distance below the outfall. The zone of a stream in which there exist significant variations of concentration in the lateral and vertical directions, is termed a "mixing zone". This definition is broader than the traditional definition of a mixing zone based on water quality criteria (i.e. zone of non-compliance) and will be used in this report.

Figure 1 shows a typical plan view of a mixing zone along with variations in cross-sectional width, depth, velocity and concentration distribution of a conservative material at various transects below the outfall. The average concentration of the material in the plume at each transect, C_{av}, is also shown in Figure 1. The concentration distribution profiles indicate that there is an attenuation of the peak and average concentration values at various transects below the outfall due to transverse dispersion of the material. A method of evaluating the attenuation of the average concentration of a conservative material by mixing in the plume is presented in Section 2.8.

2.1.2 Kinetics of Chlorine Decay

Several investigators have studied the factors affecting the decay of chlorine residual concentration both in lab experiments and in field conditions and proposed different kinetic models to describe the decay process. A study by Katz (1977) on the chlorine

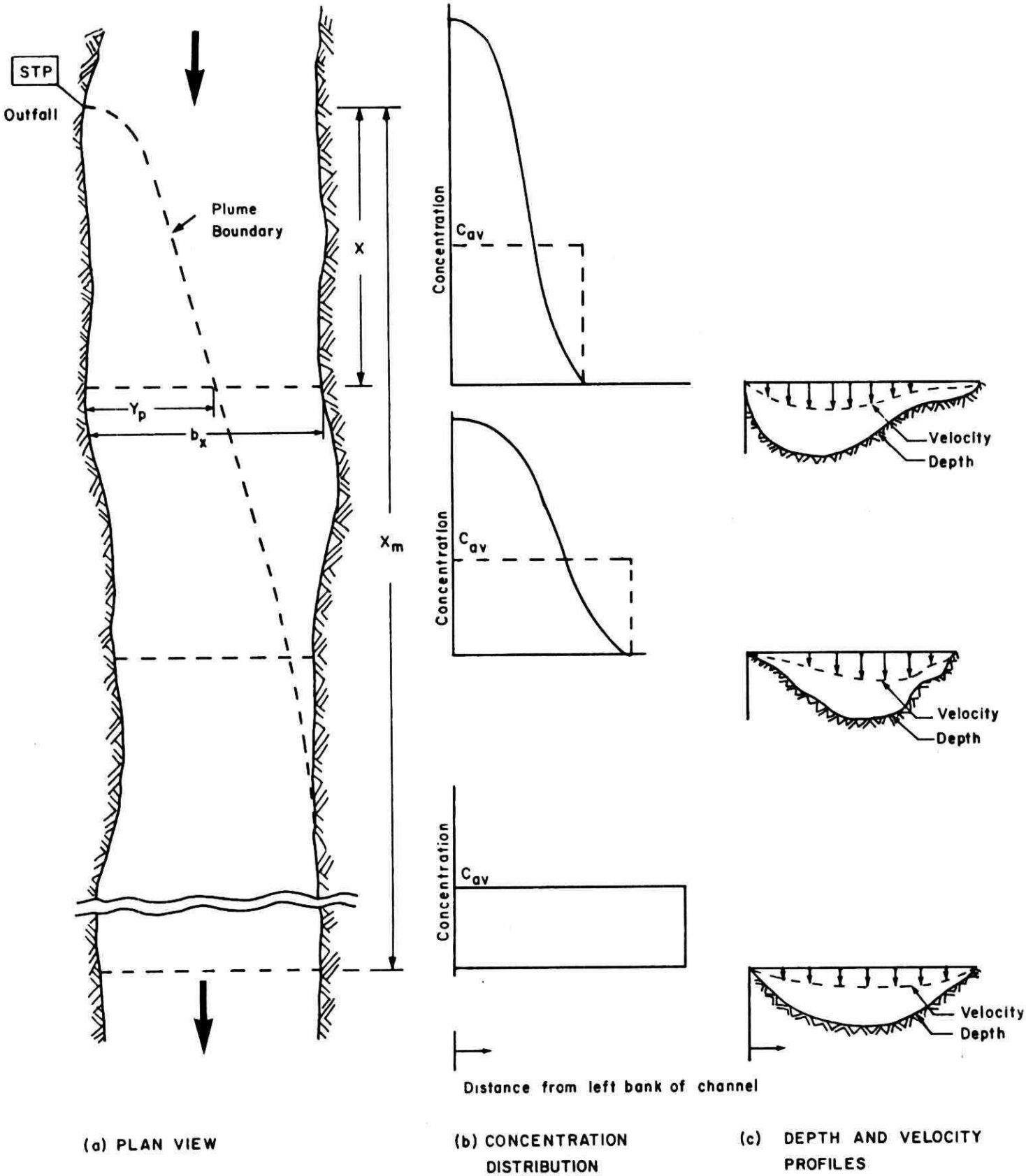

FIGURE 1. SCHEMATIC DIAGRAM OF MIXING ZONE

dissipation and toxicity in the presence of nitrogenous compounds, suggests the applicability of a first order kinetic model to describe the decay of chlorine residuals. However, Hostgaard-Jensen, Klitgaard and Pedersen (1977) felt that the decay of chlorine in cooling waters can be best represented by assuming two simultaneous reactions, one being an almost instantaneous reaction of chlorine with a component X in water, the other being a second order reaction. Laboratory investigations on chlorine residual decay in natural stream and reconstituted water samples were carried by the Water Quality Laboratory, Ministry of the Environment (Wisz, Ellis and Innis, 1977); attempts to describe the observed chlorine residual decay by the zero, first and second order kinetic models were not successful. In this investigation, a first order kinetic model is used to describe the decay of total residual chlorine concentration by chemical reaction and other physical and biochemical processes (except attenuation by mixing).

2.2 MATHEMATICAL MODEL FOR MIXING ZONES

A simplified equation applicable to the prediction of the concentration of chlorine residuals in mixing zones of shallow streams is given by the differential equation:

$$u \frac{\partial c}{\partial x} = e_y \frac{\partial^2 c}{\partial y^2} - k_d c, \qquad \ldots (1)$$

in which x and y are the longitudinal and transverse co-ordinates, respectively; c is the concentration of chlorine residual at (x,y); u is the mean velocity of flow in the x direction; e_y is the transverse dispersion coefficient; and k_d is the first order decay coefficient. The term on the left hand side of Eq. 1 represents advective transport while the two terms on the right side represent, in order, the lateral transport by dispersion and the decay of the material by chemical reaction. Equation 1 is based on the following assumptions:

1. The instream processes have attained a steady state and remain steady with time.
2. Transport of chlorine residual by dispersion in the longitudinal direction is negligible compared to the advective transport in that direction.
3. The stream is shallow and wide so that the vertical distribution of concentration is uniform at all transects.
4. The effects of secondary currents in the lateral and vertical directions are negligible.
5. The decay of residual chlorine concentration follows first order kinetic law, and there are no other sources and sinks of residual chlorine in the stream.

Analytical solutions of Eq. 1, subject to appropriate boundary conditions, are readily available in the literature for bank and diffused outfall sources (Carslaw and Jaeger, 1956, and Lau, 1972). However, for streams in which there are significant depth and velocity variations and meanders, the effects of secondary currents appear to become important. Modelling techniques applicable to such complex situations will be considered in future studies.

2.3 VARIATION OF HYDRAULIC PARAMETERS WITH FLOW

The variations in channel width, depth and velocity with flow are expressed by the Leopold-Maddock equations. If the values of width b_1, depth h_1, and velocity u_1, at a flow Q_1, are known, then b_2, h_2 and u_2 at another flow Q_2 may be calculated from the following equations:

$$b_2 = b_1(Q_2/Q_1)^p \qquad \ldots (2)$$

$$h_2 = h_1(Q_2/Q_1)^q \qquad \ldots (3)$$

$$u_2 = u_1(Q_2/Q_1)^r \qquad \ldots (4)$$

The values of the exponents p, q and r will have to be estimated using field data.

2.4 TRANSVERSE DISPERSION COEFFICIENT

The degree of mixing in the lateral direction by turbulence and cross-sectional velocity variation is expressed by the transverse dispersion coefficient, e_y. The value of e_y can be determined from transverse concentration distribution data. In the absence of such data, the value may be estimated from the relation $e_y=\alpha_e hu$, in which α_e is a dimensionless coefficient whose value varies from about 0.02 to 0.04; and h and u represent average values of depth and velocity, respectively.

Lower values of α_e are indicative of lower exchange capacities of streams and are applicable to slow moving sluggish channels; higher values of α_e indicate higher exchange capacities that are typical of shallow fast moving turbulent streams.

2.5 EFFLUENT PLUME WIDTH

In the case of bank outfalls, and diffused outfalls with a diffuser length much smaller than the channel width, the width of a plume, y_p, at a transect distant, x, from the source is assumed to follow an empirical relation expressed by the following non-dimensional equation:

$$\frac{y_p}{b_x} = a\left(\frac{x}{x_{\frac{1}{2}}}\right)^m ; \qquad \left(y_p \leq b_x\right) \quad , \qquad \ldots (5)$$

in which b_x = width of channel at a transect distant x from the source; $x_{\frac{1}{2}}$ = distance from the source to a transect where the plume width is equal to one half of the channel width; a = 0.5 (by

definition). The values of m and $x_{\frac{1}{2}}$ will have to be evaluated from field data analysis. Equation 5 is similar in form to the empirical expressions used to describe the spread of wakes and jets (Hinze, 1959).

The plume width predicted by Eq. 5 represents the average plume boundary of a conservative material (e.g. chlorides). The plume width of residual chlorine will be within the value of width predicted by Eq. 5.

2.6 MIXING ZONE LENGTH

According to the definition, the mixing zone length, x_m, is the downstream distance between the outfall and the transect at which the cross-sectional concentration distribution has attained uniformity. An expression for mixing length[1] has been developed by Fischer (1967), based on a theoretical analysis of turbulent diffusion mechanisms. Using an analytical solution of the two dimensional convective diffusion equation, Ruthven (1971) obtained an expression for the mixing zone length in shallow streams, on the assumption that the variation in cross-sectional concentration distribution does not exceed an arbitrarily chosen limit. Both of these approaches have resulted in an expression of the form:

$$x_m = \alpha_m \frac{\ell^2 u}{h\, u_*} , \qquad \ldots (6)$$

in which ℓ is a characteristic length dependent on the location of source and position of maximum surface velocity within the cross-section, u_* is the shear velocity and α_m is a non-dimensional constant.

For the estimation of mixing length, Fischer suggested a value of 1.8 for the constant α_m based on laboratory test data, whereas Ruthven obtained a value of 1.3 based on a criterion of 10% variation in the cross-sectional concentration values. The characteristic length ℓ, is usually expressed as a fraction of the channel width b; the ratio ℓ/b varies from 0.5 for a source located at the centre of the channel to 1.0 for bank outfalls. The shear velocity can be calculated from the relation $u_*=\sqrt{ghS}$, where g=acceleration due to gravity and S=slope of channel bed.

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[1]Mixing length is defined as the distance below a point or line source that corresponds to the duration of an initial convective period in which the movement of a tracer cloud does not follow the one dimensional dispersion theory.

2.7 SPATIAL DISTRIBUTION OF TOTAL RESIDUAL CHLORINE

The concentration distribution of TRC at any transect below an outfall may be obtained by solving Eq. 1 subject to appropriate boundary conditions. For the case of a vertical line source of a conservative material discharged from bank and diffused outfalls, integrated solutions of Eq. 1 are presented by Carslaw and Jaegar (1956), Holley, et al (1972) and Lau (1972). Since the decay of chlorine residual concentration is assumed to follow the first order kinetic law, the solutions are to be multiplied by the term $\exp(-k_d x/u)$, where k_d is the decay rate coefficient due to chemical reaction and other mechanisms, except dispersion effects. The analytical solutions of Eq. 1 used in this study are presented in the Appendix.

In case of bank outfalls, there is an immediate lateral spread of the plume below the source due to such factors as protrusion of outfall into the river, discharge velocity of outfall, etc. The effluent mixing in such a case can be considered to be equivalent to that of a diffused outfall with a finite source width, w_s, which has to be estimated using the field data.

2.8 RELATIVE EFFECTS OF MIXING AND DECAY

If the instream residual chlorine is treated as a conservative material, it is possible to predict the cross-sectional distribution of TRC due to mixing effects only by setting $k_d=0$. A comparison of the predicted distribution with and without decay would then permit an estimation of the relative effects of mixing and decay on the attenuation of TRC concentrations.

Another method of evaluating the significance of mixing relative to decay by other mechanisms (such as chemical reactions) on the reduction of TRC is to compare the rates of decay attributable to each of these mechanisms. The concentration prediction technique described in the previous paragraph does not permit a direct evaluation of a first order attenuation rate coefficient due to mixing. Therefore, an empirical method described below has been developed to estimate an apparent attenuation rate coefficient due to mixing.

The streamflow in the plume Q_p, that dilutes the effluent at each transect is estimated from the equation:

$$Q_p = y_p \, Q_r / b_x, \qquad \ldots (7)$$

where Q_r = total streamflow. Then the average concentration of the conservative material in the plume at each transect is determined from:

$$C_{av} = C_e Q_e / Q_p, \qquad \ldots (8)$$

where C_e = concentration in effluent; and Q_e = effluent flow.

Assuming that the attenuation of TRC concentration due to dilution follows an exponential law, an apparent decay rate coefficient due to mixing, k_p, can be determined from a plot of (log C_{av}) vs distance (or time of travel).

The gross decay rate of TRC k_t, due to mixing, chemical reaction and other instream processes can be determined from a semi-log plot of the observed average TRC concentration vs. distance (or time of travel). The decay rate k_d, due to chemical reactions and other processes (except mixing) can then be determined from the relation $k_d=(k_t-k_p)$.

It should be noted that the attenuation of concentration attributable to the transverse dispersion process is expressed by the apparent decay rate coefficient, k_p, in order to evaluate the first order decay rate coefficient, k_d. The value of k_p would vary with the transverse dispersion characteristics and hence is unsuitable for prediction of concentration distribution under various streamflow conditions.

2.9 TEMPERATURE EFFECTS

The effect of temperature on the decay rate coefficients is usually represented by the following form of the van't Hoff-Arrhenius relationship (Fair and Geyer, 1961):

$$k_{d_2} = k_{d_1} \exp\left\{\frac{E(T_2-T_1)}{RT_1T_2}\right\} , \qquad \ldots (9)$$

in which k_{d1} and k_{d2} are the rate coefficients at temperatures T_1 and T_2 (expressed in ^oK) respectively; R is the gas constant (1.99 cal per ^oC); and E is a constant characteristic of the reaction termed "activation energy". The higher the value of E, the slower is the reaction. In practice, the value of the term (E/RT_1T_2) tends to attain a narrow range. Because of this fact, Eq. 9 can be written in a modified form as follows:

$$k_{d2} = k_{d1}\theta^{T_2-T_1} \qquad \ldots (10)$$

where $\theta=(E/RT_1T_2)$ is a temperature correction factor. The values of activation energy E for reactions involving aqueous chlorine and chloramines at room temperature usually lie in the range 10,000 to 20,000 cal. In sewage disinfection practice, the residual chlorine is mostly in the form of chloramines. Using the values of E at different values of pH normally encountered in practice (Fair and Geyer, 1961) the values of θ at various temperature values were computed and are summarized in Table 1. Thus, the value of θ is seen to lie in the range 1.025 to 1.031 for the pH range 7.0 to 8.5 and temperature range 4^oC to 25^oC, normally encountered in natural streams. For practical purposes, the temperature dependence of chlorine residual reaction rate coefficient can thus be expressed by Eq. 10 by taking $\theta=1.03$.

TABLE 1: TEMPERATURE CORRECTION FACTORS

pH Units	E Calories	T_1 °C	T_1 °K	T_2 °C	T_2 °K	θ
7.0	12,000	4	477	4	477	1.027
7.0	12,000	25	498	25	498	1.025
8.5	14,000	4	477	4	477	1.031
8.5	14,000	25	498	25	498	1.029
8.5	14,000	4	477	25	498	1.030
9.5	20,000	4	477	4	477	1.045
9.5	20,000	25	498	25	498	1.041

2.10 COMPUTER MODEL

A computer model HGDISEF has been developed to predict the transverse distribution of concentration at various transects using the relationships described in Sections 2.3, 2.4, 2.5, 2.7 and 2.9. The program incorporates point source (bank outfall) as well as finite width (diffused) source models; the origin of both sources is placed at the outfall shore. The program can be used to predict the concentration distribution of a conservative or non-conservative material, the option being determined internally by the value of the decay rate coefficient. If the transverse dispersion coefficient is zero, the model simplifies to the plug flow case.

The input data includes the number of transects, channel hydraulic and plume width parameters, length of diffused outfall, transverse dispersion coefficient, decay rate coefficient, temperature, streamflow, effluent flow rate and concentration of TRC in the effluent. There are options built into the program to vary any desired input parameter.

The output consists of a table of lateral distances from shore and corresponding concentration values at each transect, and includes predictions from both point source as well as finite width source models, as well as plume width values predicted from Equation 5. The one third width concentration values at each transect are also tabulated in the output matrix.

Further details of the computer program are provided in the Appendix including a description of the variable names, program listing and a sample input and output.

III FIELD STUDIES

3.1 DESCRIPTION OF STUDY AREA

Investigations were carried out in four shallow streams located in southern Ontario. The details of these investigations are presented by Wisz, Ellis and Inniss (1977). Data collected in the following streams are used in the analysis presented in this report:

Boyne River below Alliston STP outfall;
Aurora Creek below Aurora STP outfall.

Schematic layouts of the streams are shown in Figure 2. The channel alignment of the Boyne River in the study location is straight with the presence of a few flat bends; the alignment of the Aurora Creek channel is marked by the presence of several sharp bends. The bed material in both streams is made up of silt, sand and boulders.

The Boyne River flows into the Nottawasaga River; the distance between the Alliston STP outfall and the confluence of the two streams is approximately 2.9 km. The mean annual daily flow in the Boyne River upstream of the Alliston STP is 1.62 m^3/sec and the minimum daily flow is reported to be 0.11 m^3/sec based on 1968-70 data. Effluent from a food processing industry (Salada Foods) is discharged into the creek at about 945 m below the Alliston STP outfall.

Aurora Creek is a tributary of the East Holland River; the channel length between the Aurora STP outfall and the Holland River is about 4.8 km. Seasonal streamflow measurements in the creek indicate that the flow varies from 0.10 m^3/sec to about 0.50 m^3/sec. A small unnamed creek enters Aurora Creek about 1.6 km below the Aurora STP outfall.

3.2 DATA COLLECTION ASPECTS

During the field investigations, data on channel geometry, flow rates, time of travel and effluent dispersion characteristics were collected. Instream residual chlorine levels at various distances below the outfall were measured during a preliminary run. Based on these data, several transects were established in the stream for sampling purposes. At some of the transects below the outfall, cross-sectional sampling points were located based on the effluent dispersion characteristics in order to collect data on lateral variations of water quality parameters including residual chlorine concentrations. The details of field data at each location, including the number of sampling runs and parameters measured are presented by Wisz, Ellis and Inniss (1977). A brief summary of the field data is presented below.

An intensive field survey was carried out in the Boyne River during August 11-12, 1976. During the survey, the streamflow in the Boyne River upstream of the Alliston STP was measured at 0.78 m^3/sec and the average instream temperature was 21.5^{o}C; the average STP effluent flow rate was 39.6 L/sec. The average concentrations of total residual chlorine and chloride at various sampling points for the duration of the survey are summarized in Table 2.

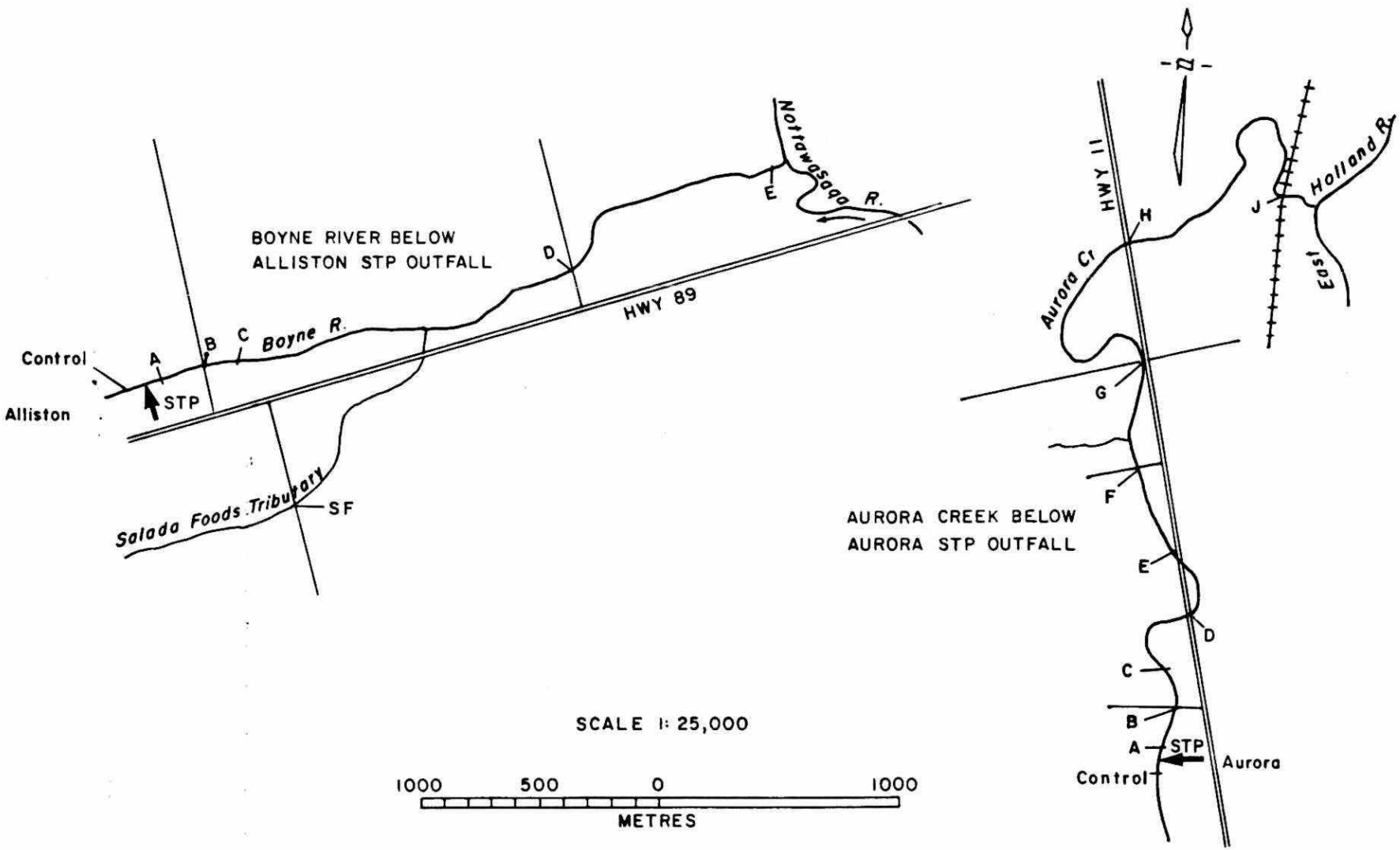

FIGURE 2. SCHEMATIC LAYOUT OF STUDY AREAS.

TABLE 2: SUMMARY OF BOYNE RIVER FIELD SURVEY DATA - AUGUST 11-12, 1976

Transect and Sampling Station	Distance below Outfall m	Transverse Distance below Outfall Bank m	Avg[a] TRC ug/L	Avg Chlorides[a] as Cl^- mg/L
Control			0	13.7
Effluent	0		1170	131.0
Transect A	21	8.84[b]	100[c]	
$A\frac{1}{2}$		0.381	220	47.0
A1		0.76	18	27.0
A2		1.52	0	16.2
A3		2.29	0	14.4
A4		4.88	0	13.6
A5		6.71	0	13.6
Transect B	61	10.70[b]	16[c]	
B1		1.52	23	24.3
B2		3.05	10	20.4
B3		4.57	2	17.0
B4		7.62	0	13.6
B5		9.45	0	13.4
Transect C	183	6.40[b]	3[c]	
C1		1.22	6	20.0
C2		2.44	3	19.0
C3		3.66	1.4	17.0
C4		4.88	0.6	15.0
Salada Foods Outfall	945		0	21.0
Transect D	1148		0	18.0
Transect E	2897		0	17.0

[a]Average concentration of five samples taken over a duration of 27 hours (except three samples at $A\frac{1}{2}$).

[b]Channel width at the transect.

[c]Mean concentration in the effluent plume.

Intensive field investigations in the Aurora Creek were carried out during summer and winter. During the summer study (August 18-19, 1976), the flow in the creek upstream of the Aurora STP outfall was 0.12 m^3/sec and the average instream temperature was 18.3°C. The average effluent flow rate was 98 L/sec. The flow in the unnamed creek was not measured; however, based on a mass balance of conductivity, the flow in this creek was estimated as 0.017 m^3/sec whereas a mass balance of chlorides resulted in an estimation of 0.061 m^3/sec. During the winter study (February 9, 1977), the flow in the Aurora Creek was 0.166 m^3/sec including an effluent flow of 87.5 L/sec; the average instream temperature was 5.5°C. There was some ice cover in the lower sections of the creek. The average concentrations of TRC, conductivity and chlorides at various transects are summarized in Table 3 for the summer studies. The cross-sectional mean concentrations of TRC obtained during the winter study are also presented in Table 3.

TABLE 3: SUMMARY OF AURORA CREEK FIELD SURVEY DATA

Transect and Sampling Station	Distance below Outfall m	Channel Width m	Summer[a]: August 18-19, 1976 TRC ug/L	Conductivity umho/cm	Chloride mg/L	Winter[b]: February 9, 1977 TRC ug/L
Control			0	626	31	0
Effluent	0		1536	2190	342	2330
A	15.2	1.83	722	1353	187	1379
B	91.4	3.50[c]	615	1362	169	918
C	402.3		520	1434	172	980
D	643.7		404	1380	208	902
E	1127.0		287	1400	180	824
F	1609.0		180	1415	178	786
G	2092.0		82	1354	170	607
H	2897.0		11	1332	173	403
J	4828.0		0.8	1270	160	213

[a]Average concentration of seven samples taken over a duration of 19 hours.
[b]Average concentration of four samples taken over a duration of 10 hours.
[c]Estimated average channel width at each transect.

IV DATA ANALYSIS AND MODELLING RESULTS

4.1 BOYNE RIVER BELOW ALLISTON STP OUTFALL

To investigate the effect of streamflow variations on the total residual chlorine (TRC) distribution, the following streamflow values ranging from 0.25 m^3/sec to 1.64 m^3/sec were used. The width, depth and velocity values at various flows were computed using the following values of the exponents in Equations 2 to 4: p=0.1; q=0.5 and r=0.4. The flow and associated width, depth and velocity values are presented in Table 4. Computation of the transverse dispersion coefficient is based on α_e=0.02. The predicted mixing zone length values at the above mentioned flows with α_m=1.8 and Manning's roughness coefficient n=0.035, are presented in Table 4 for ℓ= b/2, ℓ=2b/3 and ℓ=3b/4. The mixing zone length is found to decrease with an increase in the streamflow, reflecting the effect of increase in transverse diffusion at higher flows.

In order to determine the gross TRC decay rate coefficient k_t (due to mixing and all other mechanisms), a semi-log plot of observed average TRC concentration vs. distance was prepared (see Fig. 3). An examination of the plot indicates that the rate coefficient varies significantly in the two sections as indicated by the slopes of the solid lines. The estimated rate coefficients (k_t) for the two sections are 0.27 and 0.082 per minute (to base 10), respectively, at the observed mean temperature of 21.5°C.

The plume width values were determined using the transverse distribution of chloride concentration at various transects; the values of $x_{\frac{1}{2}}$ and m were evaluated to be 59.4 m and 0.43 respectively, from a log-log plot of (y_p/b_x) vs. x.

By treating the average TRC as a conservative material, the average TRC concentration values in the plume due to mixing effects only, computed from Eqs. 7 and 8, are: 177.69, 112.65, 70.38 and 56.98 ug/L at the transects A, B, C and D respectively. Using these values, the apparent attenuation rate coefficients due to mixing (k_p) are found to be 0.069 and 0.023 per minute (to base 10) for sections AB and BC, respectively (see Figure 3), representing approximately 25% and 28% of the gross decay rate values. Thus, attenuation of TRC concentration due to mixing only accounts for about 30% of the observed decay. The corresponding decay rates of TRC (k_d) attributable to chemical reactions and other mechanisms, determined from $k_d=(k_t-k_p)$, are 0.20 and 0.059 per minute (to base 10). Since a different decay rate for each section could not be specified for the model used, an average value of k_d (obtained from model calibration) has been used in the computations.

In order to calibrate the model, several modelling runs were carried out with various combinations of k_d, α_e and w_s. Based on comparisons between the observed values of TRC and predictions of the model at various transects, it was found satisfactory to use α_e=0.02 and w_s=1.2 m. The modelling results also showed that the predicted values of both models were higher than the observations at Transect A; this may be attributed to the effect of initial mixing mechanisms since Transect A is too close to the source, being located at 21.3 m below the outfall. Therefore, the observed TRC data at Transect A were felt to be unsuitable for calibration. The

TABLE 4: BOYNE RIVER - HYDRAULIC PARAMETERS AND MIXING ZONE LENGTHS AT VARIOUS FLOWS

Flow m^3/sec	Width m	Depth m	Velocity m/sec	Mixing Zone Length*, m ℓ=b/2	ℓ=2b/3	ℓ=3b/4	Remarks
0.20	8.60	0.183	0.131	1249	2220	2813	
0.41	9.27	0.259	0.172	1086	1931	2445	
0.82	9.97	0.366	0.227	925	1646	2084	... Summer Survey Conditions
1.64	10.59	0.518	0.300	796	1415	1791	

*Using Manning's Roughness Coefficient, n=0.035.

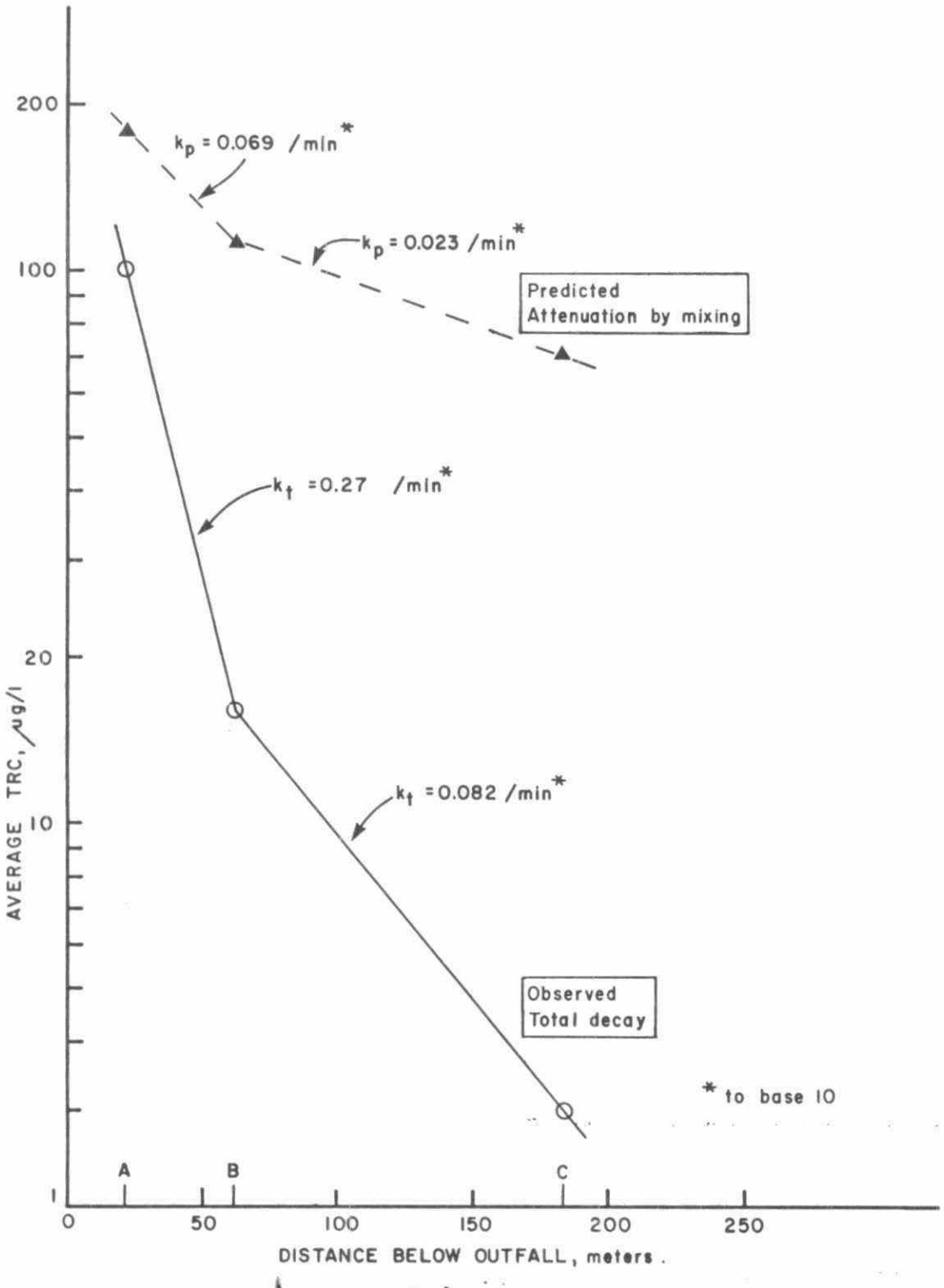

FIGURE 3. ATTENUATION AND DECAY OF TOTAL RESIDUAL CHLORINE IN BOYNE RIVER

selection of a value of k_d posed some problems. The decay rates vary significantly in two successive reaches (see Fig. 3). However, the formulation of the model assumes constant values of k_d and e_y in all the reaches, necessitating the use of a value for each coefficient that is representative of the entire study stretch of the stream. When a higher value of k_d (0.20 per minute) was used, there was a better agreement between the observations and predictions at Transect B, while the predictions at Transect C were too low. After several trials with different values of k_d (within the range of values stated in the previous paragraph), reasonable agreement between the observed and predicted values was obtained at either Transect B or Transect C, but not at both transects simultaneously. Based on these analyses, k_d=0.12 per minute (to base 10), was selected to be a representative value for the entire study stretch. With the combination of the parameters α_e=0.02, w_s=1.2 m, and k_d=0.12 per minute, the TRC values predicted by both point source and finite width source models were found to be generally higher than the observed values at Transects A and B, whereas the predicted values at Transect C were in reasonable agreement with the observations. For the purpose of further analyses, the finite width source model predictions were used; the observed and predicted values of TRC are shown in Figure 4(c).

The difficulties encountered in the calibration procedure are attributable to the assumption of constant values of k_d and e_y in the model formulation. In shallow streams with highly variable morphological characteristics, the hydraulic and biochemical processes are subject to rapid changes from one reach to another, thus rendering the assumptions of constant k_d and e_y inappropriate. This analysis brings out the need for the development of a model which allows for such variables. In spite of the limitations outlined above, the model can still be applied as a useful tool to many practical situations with the exception of those cases where the variabilities are significant, e.g. initial stream reaches immediately below the outfalls.

The TRC values predicted by the finite width source model for various streamflow values are presented in Figures 4(a)-(d). From these plots, it can be seen that the peak concentration of TRC decreases with an increase in the streamflow. The plots also indicate that the width of plume at each transect increases with the streamflow reflecting the effect of increase in transverse mixing rates at higher flows.

The variation of TRC value at the one third width point of each transect (from the outfall shore of channel) with streamflow and downstream distance, shown in Figure 5(a), indicates that the TRC value increases with an increase in the flow, even though the dilution ratios of streamflow to STP effluent flow are higher. However, as the streamflow tends to zero, the TRC values at transects close to the outfall can be expected to increase. The one third width TRC values are seen to have highest values at Transect C. The channel is narrow at this transect, having a width of 6.4 m (Table 2). If the channel width is increased to 10 m at a streamflow of 0.82 m^3/sec, the model predictions result in considerably lower values of the one third width TRC values as shown in Figure 5(b). Thus, variations in channel width, which are quite common in natural streams, appear to have an effect on the transverse distribution of the TRC concentrations.

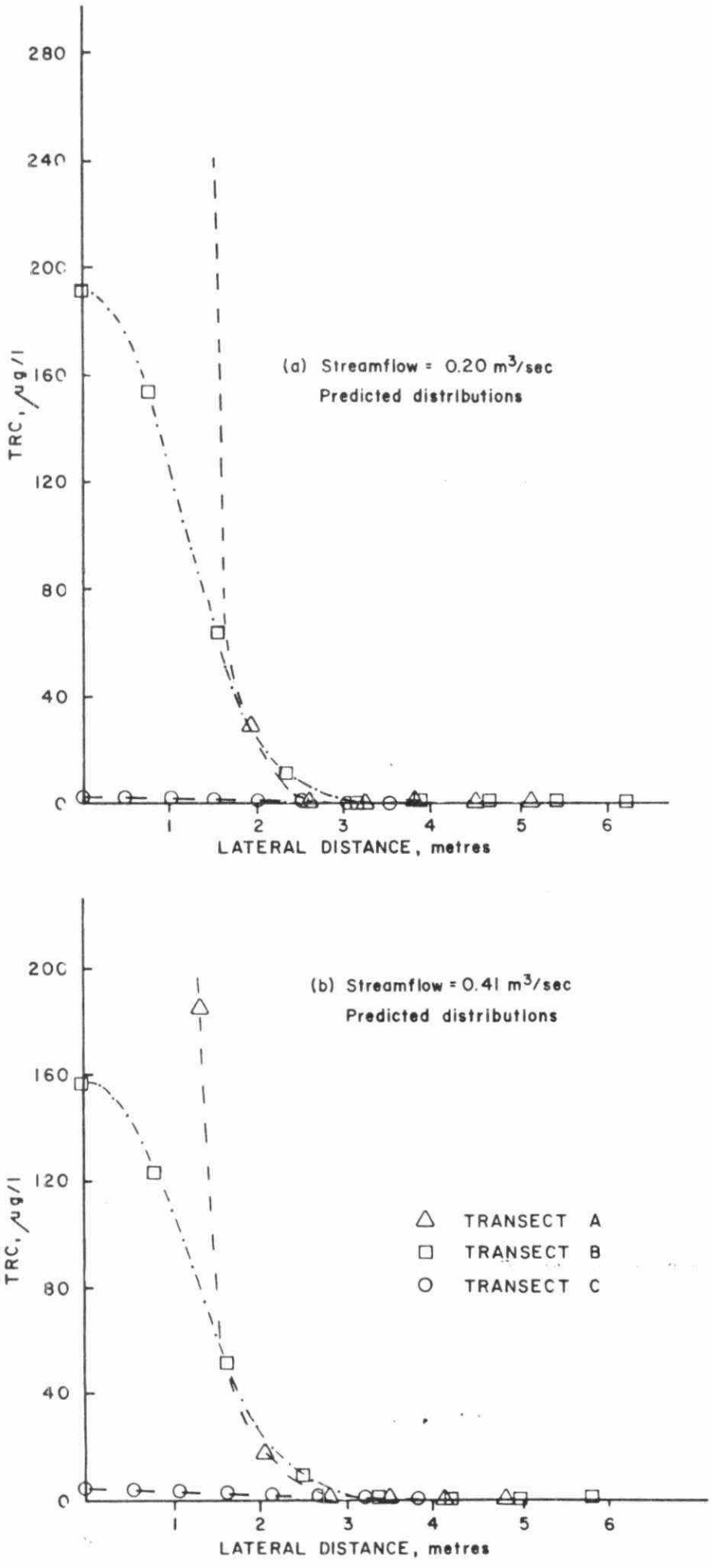

FIGURE 4. TRANSVERSE DISTRIBUTION OF TOTAL RESIDUAL CHLORINE AT DIFFERENT FLOWS IN BOYNE RIVER.

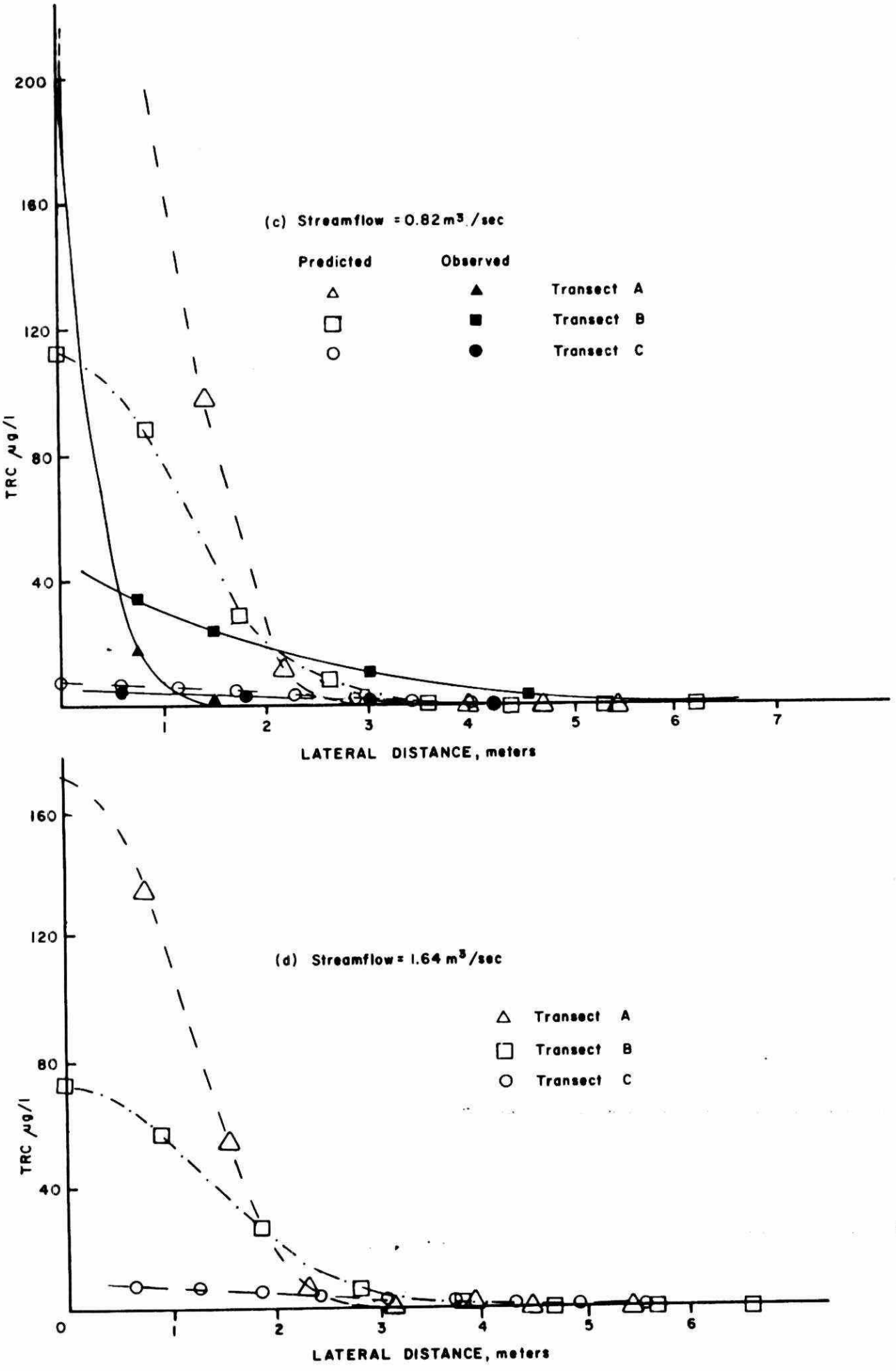

FIGURE 4. CONTINUED.

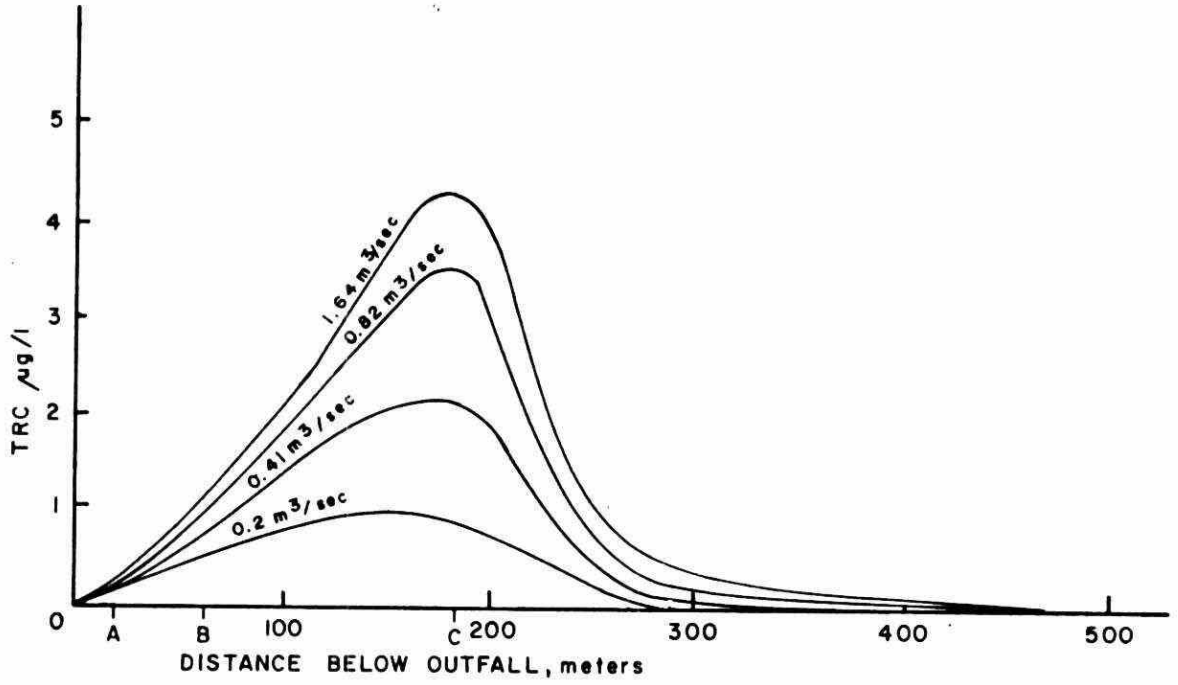

FIGURE 5 (a) LONGITUDINAL VARIATION OF ONE THIRD WIDTH PREDICT TOTAL RESIDUAL CHLORINE VALUES IN BOYNE RIVER.

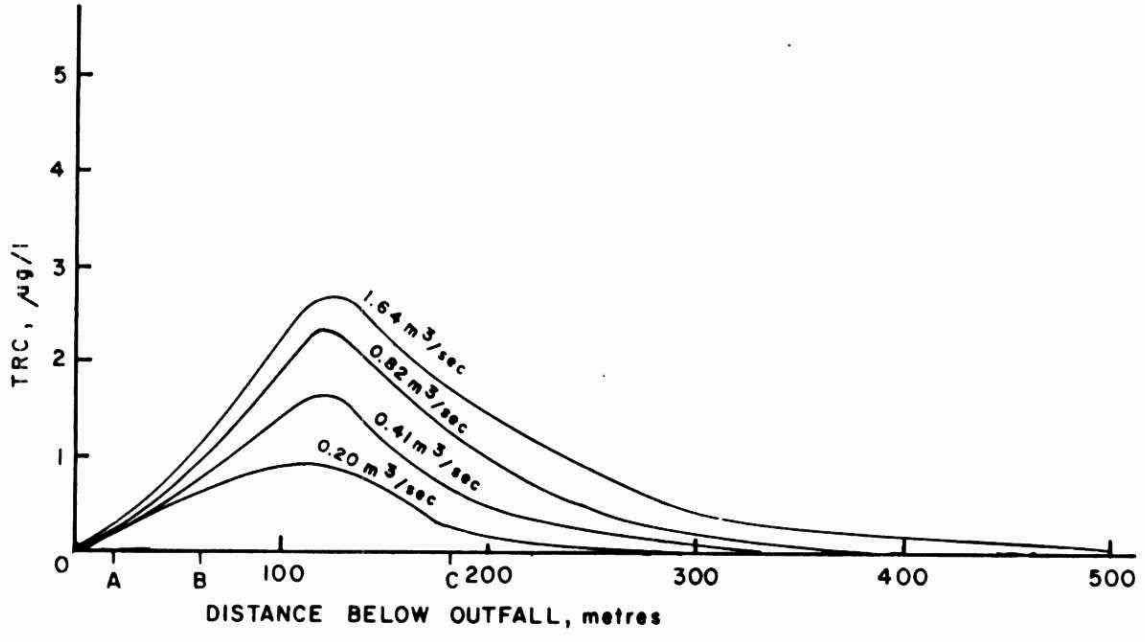

FIGURE 5(b) EFFECT OF INCREASED CHANNEL WIDTH AT TRANSECT ON ONE THIRD WIDTH PREDICTED TOTAL RESIDUAL CHLORINE VALUES IN BOYNE RIVER.

4.2 AURORA CREEK BELOW AURORA STP OUTFALL

4.2.1 Summer Study

Total residual chlorine concentrations were predicted under four streamflow conditions. The flow rates and related hydraulic characteristics of the channel are summarized in Table 5. (In Equations 2 to 4, the values of exponents used are p=0.1, q=0.5 and r=0.4). In the plume width computations, the values of $x_{\frac{1}{2}}$ and m were taken equal to 30.5 m and 0.9 respectively; this is based on the fact that the effluent (discharged from the bank outfall) spreads across the entire channel width in a distance of about 60 m below the outfall. The significance of transverse mixing was investigated by taking α_e=0.02, as well as α_e=0.0 (plug flow model). The results indicated that the effluent plume spreads across and fills the entire channel width at about 90 m below the outfall, and the cross-sectional variations in concentration are within 10% at about 500 m below the outfall. The computed mixing zone length values using α_m=1.8, Manning's roughness coefficient n=0.025 and ℓ=b/2, ℓ= 2b/3 as well as ℓ=3b/4, are presented in Table 5. The mixing zone length generally decreases with an increase in streamflow, as expected.

A semi-log plot of the cross-sectional mean of observed values of TRC vs. distance below the outfall is shown in Figure 6. The rate of change of concentration downstream of the outfall is seen to change significantly below Transect F. The decay rate coefficient is found to be 0.0052 per minute (to base 10) for the reach AF and 0.012 per minute (to base 10) for the reach FH. The decay rate below Transect F may have been affected by the inflow from the small creek. For modelling purposes, a decay rate value of 0.0052 per minute (to base 10) has been used. No attempt was made to evaluate the apparent attenuation rates of TRC due to mixing since the plume spreads across the entire channel width in a relatively short distance below the outfall.

The model calibration procedure resulted in TRC values predicted by the diffused source model being too low (for w_s=61 cm and α_e=0.02); whereas, point source model predictions were in good agreement with the observations at Transects B to F. (Note: When α_e=0, diffused source model predictions will be the same as those of the plug flow model).

As mentioned earlier, point source model predictions are based on α_e=0.02, as well as α_e=0 (plug flow model). The predictions indicated that at Transects B to E, transverse variation of TRC concentration could exist, although the effluent has filled the entire cross-section. The longitudinal distribution of TRC predicted by the plug flow model for the survey condition presented in Fig. 7 shows good agreement with the observed values at Transects B to F. The difference between the predicted and observed TRC values at Transects G and H may be due to the effects of inflow from the small creek on the decay rate coefficient. Plug flow model predictions at other flows are also presented in Fig. 7. No attempt was made to predict the one third width TRC values under different flow conditions since the cross-sectional concentration variations become too small in a relatively short distance below the outfall.

TABLE 5: AURORA CREEK - HYDRAULIC PARAMETERS AND MIXING ZONE LENGTHS AT VARIOUS FLOWS

Flow m^3/sec	Width m	Depth m	Velocity m/sec	Mixing Zone Length*, m $\ell = b/2$	$\ell = 2b/3$	$\ell = 3b/4$	Remarks
0.10	3.23	0.173	0.177	259	460	582	
0.17	3.41	0.226	0.216	230	410	519	... Winter Survey Conditions
0.22	3.51	0.259	0.244	218	387	490	... Summer Survey Conditions
0.34	3.66	0.321	0.290	198	353	446	
0.45	3.76	0.371	0.325	186	331	419	

*Using Manning's Roughness Coefficient, n=0.035.

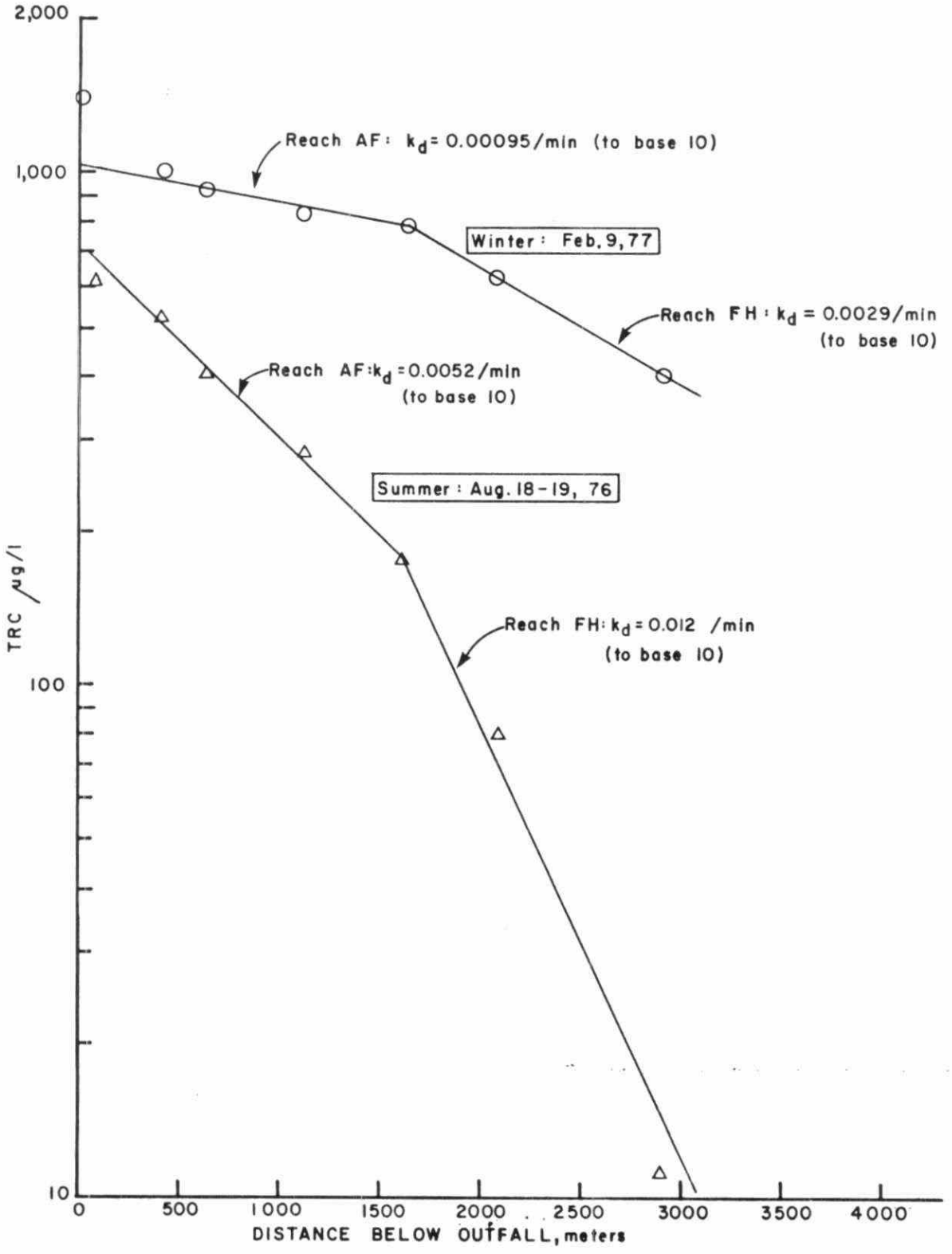

FIGURE 6. DECAY OF TOTAL RESIDUAL CHLORINE IN AURORA CREEK.

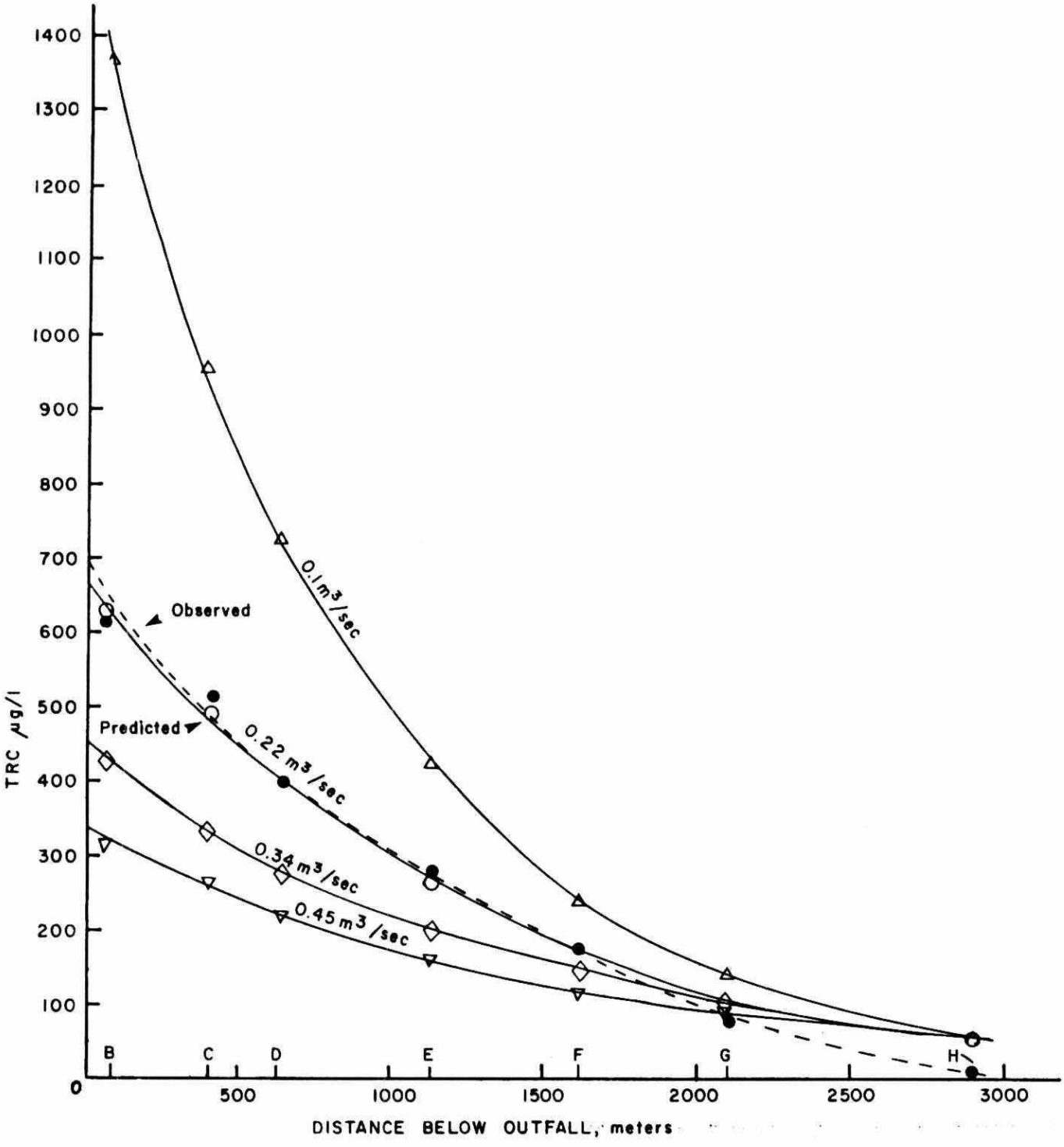

FIGURE 7. LONGITUDINAL DISTRIBUTION OF TOTAL RESIDUAL CHLORINE IN AURORA CREEK.

4.2.2 Winter Study

The possible existence of cross-sectional concentration variations between Transects A to D (as predicted by the model) was confirmed by the data collected during this study. The decay rate coefficient was evaluated from a semi-log plot of cross-sectional mean value of TRC vs. distance below the outfall (Fig. 6). The rate of change of concentration is seen to increase significantly below Transect F as well as below Transect H, as in the case of the summer study. However, the concentration values at Transects A and B deviate from the line of best fit. The decay rate is 0.00095 per minute for the reach AF and 0.0029 per minute for reach FH (to base 10). Prediction of the instream TRC levels under various flow conditions was not undertaken.

4.2.3 Temperature Effects

The value of the temperature correction factor was evaluated from Eq. 10 using the results of the summer and winter studies. The values of θ were found to be 1.14 and 1.12 based on the decay rates of the reach AF and of the reach FH, respectively. These values are much higher than the theoretical values given in Table 1. However, these values should be treated as tenative since they are derived from limited data.

4.3 DISCUSSION OF RESULTS

The evaluation of model parameters and calibration of the model are based on data of one field survey at each location. The value of transverse dispersion coefficient was assumed because of limited data on effluent dispersion characteristics. The calibration of the model posed some problems due to the necessity to use the same values of some of the coefficients for all reaches to conform with the assumptions involved in the formulation of the model, as well as some of the limitations associated with the available data. In case of the Boyne River, the model predictions satisfactorily represented the observed values of TRC at Transect C only; there were significant differences between the predicted and observed values of TRC at Transects A and B. In case of the Aurora Creek, there was good agreement between the observed and predicted values of TRC at Transects B to F; the model predictions did not satisfactorily represent the observed data at Transects A, G and H. The effects of the characteristics of stream and wastewater, stream turbulence, etc. on the decay of instream chlorine residuals also need to be investigated and included in the modelling procedure. These limitations should be taken into consideration in the interpretation and use of the results presented in this report. Nevertheless, this investigation has unveiled some interesting results which have significant implications on the management of water quality in effluent mixing zones. A discussion of some of the important aspects is presented below.

The expression for effluent plume width (Eq. 5) is written in non-dimensional form to account for possible variations in the plume width in proportion to the channel width in natural streams. Field

data collected during effluent dispersion studies in the Grand River below Waterloo STP indicate that there is some justification for the above-mentioned assumption. However, a modification of the expression by including transverse dispersion parameters, and further testing and validation may be required.

Using the concentration prediction results with $k_d=0$ (conservative material), it is found that the cross-sectional concentration distribution approaches uniformity at about 915 m in the Boyne River and 500 m in the Aurora Creek. These estimates are found to agree well with the predicted mixing zone length values of 925 m with $\ell=b/2$ in the Boyne River, and 490 m with $\ell=3b/4$ in Aurora Creek. Thus the ratio ℓ/b in each stream has a different value although both streams have bank outfalls.

The effect of transverse mixing in the Boyne River is estimated to cause about 30% diminution of average plume concentration of TRC under survey conditions. Since the observed concentration distributions result from the combined effects of dispersion and chemical reaction processes, it is essential that the effects of dispersion on the concentration values are separated when kinetic models are used to evaluate the decay rate coefficients using the observed data.

The finite width model predictions of instream TRC concentrations in the Boyne River indicate that at higher flows, residual chlorine is propagated to greater downstream distances. Referring to Figure 5, the one third width TRC value is seen to increase at some transects at higher flows; this is contrary to the belief that at higher flows dilution ratios are higher and hence, concentrations are lower. This phenomenon can be attributed to the following facts: At a higher flow the time of travel to a given transect is lower; consequently, the mass of residual chlorine remaining at that transect is higher since the decay of mass due to chemical reaction is proportional to $\exp(-k_d t)$. However, the transverse coefficient is higher at a higher flow, resulting in an increased transverse spread of the material present in the stream. Thus, the one third TRC value increases at a higher flow due to combined effects of increased mass remaining and increased transverse spreading. Ultimately, the one third width TRC value would start to decrease at some downstream point at which reduction of the mass by chemical decay becomes significant. This analysis suggests that higher streamflows do not necessarily provide safer zones for fish passage.

The variations in channel width at various transects may also affect the lateral distributions of concentration, and hence, the lateral boundary of the zone of passage. In the Boyne River, the channel is narrower at Transect C compared to the widths at other transects (Table 2). Referring to Figures 5(a) and (b), it can be seen that the one third width predicted TRC values would be significantly lower at Transect C if the channel at the transect is widened to 10 m from 6.4 m at a streamflow of 0.82 m^3/sec. There are several assumptions inherent in an analysis of this nature, and hence the results have limitations. However, it is presented in this report to identify the importance of an aspect of natural stream morphology in water quality investigations.

In the Aurora Creek, the effluent plume was found to spread across the entire channel in a short distance below the outfall during the summer survey; the cross-sectional concentration distribution is likely to have attained uniformity in a distance of 500 m below the outfall (based on mixing zone length values). Thus, it is reasonable to assume that the one third width TRC values are very close to the cross-sectional average values at all transects downstream of the predicted mixing zone length. Referring to Figure 7, the predicted average TRC concentration values are seen to decrease with increased flow up to Transect H, i.e., 2897 m below the outfall.

V SUMMARY AND CONCLUSIONS

The report outlines the development of a methodology applicable to investigate the persistence of total residual chlorine (TRC) concentrations in streams receiving sewage effluent, including two case studies. The relative effects of dispersion and chemical reaction processes on the reduction of instream TRC values are examined. The application of two dimensional steady state models to predict instream TRC levels is described. The effect of variation of streamflow on the TRC levels at the lateral boundary of the mixing zone has been investigated. The temperature dependence of decay rates of TRC has been examined. The assumptions and limitations of the techniques involved in the methodology are discussed.

A listing of the computer program HGDISEF used in this investigation is included in the Appendix. The program includes both point source (bank outfall) and finite width source (diffused outfall) models. The data requirements and typical input and output of the model are also included in the Appendix.

The field data collection methodology was generally satisfactory; however, it would be desirable to collect data at more transects for more detailed modelling purposes. Further details on equipment and data collection aspects are described by Wisz, Ellis and Innis (1977).

Using the methodology presented in this report, it is possible to predict the magnitude and extent of persistence of instream residual chlorine concentration at various streamflow and temperature conditions. The implications of various alternatives available for reducing TRC concentrations can be evaluated using the predictive techniques presented here. Such procedures would aid the selection of a suitable method of minimizing the impact of the residual chlorine on the water quality of receiving streams. The models presented in this report are useful tools in the evaluation of various options involved in the design of new outfalls in streams and rivers.

The following conclusions are made based on the results of this investigation.

1. The chlorine residual in the Aurora Creek is found to persist for about 4.8 km below the outfall during summer as well as winter; whereas in the Boyne River, the residuals disappeared in less than 945 m below the outfall during summer.

2. Transverse dispersion of effluent in the Boyne River is estimated to cause a reduction of about 30% of the average TRC concentration in the effluent plume under survey conditions.

3. The observed first order decay rates in the Boyne River during summer were 0.27 and 0.082 per minute (to base 10) in two successive reaches; in the Aurora Creek, the decay rates were 0.0052 and 0.012 per minute (to base 10) during the summer, and 0.0095 and 0.0029 per minute (to base 10) during the winter, in two successive reaches of the stream. The decay rates in the Boyne River were obtained from limited data and hence, they should be considered tentative.

4. Model predictions indicate that at some downstream transects, the TRC concentration at the lateral boundary of the allowable zone of non-compliance (i.e. one-third width) could increase at higher flows, contradicting the belief that the concentrations would be lower at higher flows. This is attributed to the decrease in time of travel and increase in transverse dispersion at higher streamflow.

5. The temperature correction factor θ for TRC, determined from the van't Hoff-Arrhenius relationship, is found to vary from 1.025 to 1.045 in a temperature range of 4 to 25°C and a pH range of 7 to 9.5 units. Based on field data, the temperature correction factor is estimated to be 1.12 to 1.14; however, these values may not be representative due to limitations in the field data.

6. The model needs to be improved by including reach dependent dispersion and reaction rate coefficients in order to overcome the difficulties encountered during the model calibration. However, the present model can still be applied to streams in which the coefficients in different reaches do not vary significantly.

VI RECOMMENDATIONS

The results of this investigation have shown that dispersion characteristics have a significant effect on the attenuation of instream TRC levels. The results of field investigations and data analysis indicate that the decay rate coefficients and the persistence of instream TRC concentrations vary considerably from one stream to another. This may be attributed to the characteristics of sewage effluent and of stream water, and instream processes including dispersion, reaeration and the reaction of chlorine with such compounds as ammonia, phenol, etc. Temperature is one of the most important factors affecting the reduction of instream TRC concentrations. The distribution of instream TRC concentration is also influenced by the morphological and hydraulic characteristics of the channel including variations in streamflow caused by withdrawal of water, tributary inflow, ground water recharge and discharge, etc. In order to develop predictive models which include all of these processes and factors, it is recommended that the following investigations be carried out:

1. Investigation of the effects of sewage effluent and stream water quality characteristics on the reduction of TRC levels.

2. Investigation of the effect of hydraulic characteristics of streams on the kinetic rate coefficients.

3. Further studies on the temperature dependence of the decay rate coefficients.

4. Development of predictive models applicable to natural streams to take into account the results of the above-mentioned investigations, and morphological and hydraulic characteristics of the channel.

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APPENDIX

A. Analytical Solutions

B. Computer Program - HDGISEF

B.1 Description of Variable Names

B.2 Units

B.3 Listing of Program

B.4 Sample Input and Output

A. ANALYTICAL SOLUTIONS

Solution for Point Source :

$$c(x,y) = \frac{Q_e C_e}{bhu} \exp\left(\frac{-k_d x}{u}\right)\left\{1 + 2\sum_{j=1}^{\infty} \frac{\cos(j\pi y/b)}{(1+\phi_j)^{1/2}} \exp\left[\frac{ux}{2e_y}\left\{1-(1+\phi_j)^{1/2}\right\}\right]\right\}$$

where $\phi_j = \left(\frac{2j\pi e_y}{bu}\right)^2$

Solution for Finite Width Source:

$$c(x,y) = \frac{Q_e C_e}{2huw_s} \exp\left(\frac{-k_d x}{u}\right)\left\{\text{erf}\left(\frac{w_s - y}{\psi}\right) + \text{erf}\left(\frac{w_s + y}{\psi}\right) + \sum_{n=1}^{\infty}\left[\text{erf}\left(\frac{2nb + w_s + y}{\psi}\right) - \text{erf}\left(\frac{2nb - w_s + y}{\psi}\right)\right.\right.$$

$$\left.\left. + \text{erf}\left(\frac{2nb + w_s - y}{\psi}\right) - \text{erf}\left(\frac{2nb - w_s - y}{\psi}\right)\right]\right\}$$

where $\psi = 2\sqrt{xe_y/u}$

and erf( ) is the error function defined by

$$\text{erf}(s) = \frac{2}{\sqrt{\pi}} \int_0^s e^{-v^2} dv$$

The following notations are used in the analytical solutions:

b=channel width

c=concentration in stream at a point (x,y)

C_e=concentration in the effluent

e_y=transverse dispersion coefficient

h=depth of water in stream

k_d=kinetic rate coefficient

n=number of images

Q_e=effluent flow rate

u=velocity of streamflow

w_s=width of diffused outfall

x=longitudinal distance below outfall

y=lateral distance from outfall bank side

B. COMPUTER PROGRAM - HGDISEF

B.1 DESCRIPTION OF VARIABLE NAMES

Input Variables:

TITLE: Title of study

NTR: No. of transects

NY: No of strips of equal width at transects

X: Longitudinal distance to a transect below outfall, x

BST: Channel width at a transect at reference streamflow

QRS: Reference streamflow

XHALF: Distance below outfall at which plume width is one-half of channel width, $x_{\frac{1}{2}}$

PLN: Exponent in plume width equation, m

BS: Average channel width of study stretch at reference streamflow, b

HS: Average channel depth of study stretch at reference streamflow, h

US: Average velocity at reference streamflow, u

BEX: Width exponent, p

HEX: Depth exponent, q

UEX: Velocity exponent, r

WS: Length of diffused outfall, w_s

COEFEY: Non-dimensional coefficient of lateral dispersion equation, α_e

COEFT: Temperature correction coefficient, θ

TEMPS: Temperature, ^{o}C at which reaction rate coefficient is known

RKS: First order reaction rate coefficient, k_d

QRVR: Design streamflow

TMP: Design temperature

CSPNT: Effluent concentration, C_e

QSTP: Effluent flowrate, Q_e

Output Variables:

NO: Serial No. (Col. 1)

Y: Transverse distance from shore (Col. 2)

CPT: Predicted concentration - point source model (Col. 3)

RPT: Ratio of CPT to maximum concentration at the transect (Col. 4)

CDF: Predicted concentration - finite width source model (Col. 5)

RDF: Ratio of CDF to maximum concentration at the transect (Col. 6)

EY: Transverse dispersion coefficient

B.2 UNITS

Length)
Width) -meter
Depth)

Velocity - meter per second

Streamflow - m^3 per second

STP flow - m^3 per second
Transverse dispersion coefficient - m^2 per second

Reaction Rate - per second, to base e

Temperature - ^oC

Concentration - mg/l or ug/l or other units

Note: The unit of output concentration is the same as the unit of input concentration

B.3 LISTING OF PROGRAM

```
 HEDISEF
C         * * TWO DIMENSIONAL MODEL FOR PREDICTION OF CONCENTRATION
C         DISTRIBUTION IN MIXING ZONES IN RIVERS BELOW STP OUTFALLS
C         * * PROGRAM NAME: DISEF
C         * : PROGRAMMER: T.P.H.DUNN, RIVER SYSTEMS UNIT
          DIMENSION  X(100),BST(100),B(100),YP(100),DESC(200),CYP(200)
     20   WRITE (6,40)
     40   FORMAT(/' ENTER TITLE OF STUDY')
          READ(5,2)TITLE
      2   FORMAT(20A4)
          WRITE(6,44)
     44 FORMAT(2X,'ENTER VALUES OF NTR & NY')
          READ(5,*) NTR,NY
          WRITE(6,43)
     43 FORMAT(2X,'ENTER VALUES OF X & BST,* NTR PAIRS')
          READ(5,*)(X(I),BST(I),I=1,NTR)
          WRITE (6,42)
     42 FORMAT (2X,'ENTER: QRS,XHALF,PLN,BS,HS,US,BEX,HEX,UEX')
          READ(5,*) QRS,XHALF,PLN,BS,HS,US,BEX,HEX,UEX
     22 WRITE(6,72)
     72 FORMAT(2X,'ENTER: WS,QUEFEY,QUEFT,TEMPS,RKS')
          READ(5,*)WS,QUEFEY,QUEFT,TMPS,RKS
     10   FORMAT(' * * * PLUG FLOW MODEL: NONCONSERVATIVE MATERIAL * * *')
     12   FORMAT(' * * * DISPERSION MODEL: CONSERVATIVE MATERIAL * * *')
     14   FORMAT(' * * * DISPERSION AND DECAY MODEL: NONCONSERVATIVE MATERI
         1AL * * *')
     16 FORMAT('**********************************************************')
          IRUN=0
          JY=NY+2
     60 IRUN=IRUN+1
          WRITE(6,77)
     77   FORMAT(/,' IF YOU WANT ONE-THIRD WIDTH VALUES ONLY ENTER NOPTN=77;
         *OTHERWISE ENTER 0'/)
          WRITE(6,46)
     46 FORMAT(2X,'ENTER VALUES OF QRUR,TMP,QSPNT,QSTP,NOPTN')
          READ(5,*) QRUR,TMP,QSPNT,QSTP,NOPTN
          IF(IRUN.GE.2)GO TO 79
           WRITE (6,16)
           IF (QUEFEY.EQ.0.0) WRITE(6,10)
           IF(RKS.EQ.0.0) WRITE(6,12)
           IF (QUEFEY.GT.0.0.AND.RKS.GT.0.0)WRITE(6,14)
           WRITE (6,16)
     79   QRD=QRUR/QRS
          BHU=BS*QRD**BEX
          HHU=HS*QRD**HEX
          UHU=US*QRD**UEX
           QINF=(QSPNT*QSTP)/QRUR
           QSDF=(QSPNT*QSTP)/(HHU*UHU*US)
           EY=(QUEFEY*HHU*UHU
           RK=RKS*QUEFT**(TMP-TMPS)
           WRITE(6,48)IRUN,EY,QSDF,WS,TMP
     48 FORMAT(//2X,'RUN #:',I2,2X,'EY=',F8.4,2X,'QSDF=',F7.1,2X,'WS=',
         1F4.1,2X,'TEMPR= ',F5.2)
          WRITE(6,62) QRUR,BHU,HHU,UHU
     62 FORMAT(2X,'U= ',F7.2,2X,'B= ',F7.2,2X,'H= ',F7.2,2X,'U= ',F7.2)
```

```
      DO  25 I=1,NTH
      B(I)=BS(I)*UHTO**EX
       PXH=X(I)/XHALF
       YP(I)=0.5*B(I)*(PXH**PLN)
       IF(YP(I).GT.B(I)) YP(I)=B(I)
       WRITE(6,30) I,X(I),B(I),YP(I)
30  FORMAT( /2X,'TRANSECT: ',I2,3X,'X= ',F7.1,2X,'CHANNEL WIDTH= ',F7
     1.2,2X,'PLUME WIDTH= ',F7.2//4X,'NO.',5X,'Y',6X,'CPT',5X,'EPT',6X,'
     2CDF',5X,'RDF'/)
       Y=B(I)/NY
       PUX=X(I)*WK/UHU
       PSI=2.0*SQRT(EY*X(I)/UHU)
      DO 24 J=1,JY
C *** CONTINUOUS POINT SOURCE MODEL ***
C   REF: F.A. HALLEY, ET AL., J. HYDRAULIC RESEARCH, VOL.10,1972,P.27
      IF(NOPTN.EQ.77.AND.J.GE.2) J=JY
      SUMP =0.
      IF(EY.LE.0.0) GO TO 52
      JJ=J-1
      YJ=Y*JJ
      IF (J.EQ.JY) YJ=B(I)/3
       N =0
      IF(N.GE.50) GO TO 52
50    N =N +1
       BETA=1.0+(6.2857*N*EY/(BHU*UHU))**2
       GAMA=SQRT(BETA)
       YNB=3.1429*N*YJ/BHU
       BCYS=COS(YNB)/GAMA
       UEG=UHU*(1-GAMA)*X(I)/(2.0*EY)
       SERS=BCYS*EXP(UEG)
       SUMP=SUMP+SERS
       IF(SERS.GE.0.001.OR.SERS.LE.-0.001)GO TO 50
52    CYP(J) =CINF*(1+2.0*SUMP)*EXP(-RUX)
      IF(J.LE.1.OR.J.EQ.JY) GO TO 53
      IF(CYP(J).LE.0.OR.CYP(J).GT.CYP(JJ)) CYP(J)=0.
53    CYPNT=CYP(J)
       IF(J.EQ.1)CPMAX=CYPNT
       CRPNT=CYPNT/CPMAX
      IF(EY.LE.0.0) GO TO 54
C *** DIFFUSED SOURCE MODEL ***
C   REF: Y.L. LAU, WATER RESEARCH, VOL.6, 1972,PP.749-757.
       R1=(WS+YJ)/PSI
       R2=(WS-YJ)/PSI
       CR1=ERF(R1)
       CR2=ERF(R2)
       CRSM=CR1+CR2
       II=1
   54  YIP=2.*(I*BHU
       NPSI=(YIP-WS-YJ)/PSI
       IF(NPSI.GE.2.) GO TO 66
       R3=(YIP+WS+YJ)/PSI
       R4=(YIP-WS+YJ)/PSI
       R5=(YIP+WS-YJ)/PSI
       R6=NPSI
       CR3=ERF(R3)
       CR4=ERF(R4)
```

```
01110          CR5=ERFTR5)
01120          CR6=ERFTR6)
01130          CRSM=CRSM+CR2-CR4+CR5-CR6
01140          II=II+1
01150          GO TO 64
01160     66   POSDF=CRSM*EXPT-RUN)/2.
01170          IF(J.GE.2)GO TO 68
01180          CLMAX=POSDF*OSDF
01190     68   CRDF=POSDF*OSDF/CLMAX
01200          CYDF=CRDF*CLMAX
01210         IF (J.EQ.J7) WRITE(6,38)
01220    24   WRITE(6,24) J,YJ,CYPNT,CRPNT,CYDF,CRDF
01230    54   IF (EY.GT.0) GO TO 26
01240         YJ=B(I)/2.0
01250         WRITE(6,32) J,YJ,CYPNT,CRPNT
01260     26 CONTINUE
01270     32 FORMAT (5X,I2,3X,F5.1,F9.2,2X,F6.4)
01280     34 FORMAT(5X,I2,3X,F5.1,2X,F7.2,2X,F6.4,2X,F7.2,2X,F6.4)
01290    38   FORMAT(3X,'VALUES AT B/2')
01300         WRITE (6,36)
01310     36 FORMAT(/2X,'TO CHANGE ORUR,TMP, CRPNT,DSTP, ENTER 1; IF NOT TYPE 0
01320        *')
01330         READ(5,*)NEWHYD
01340         IF (NEWHYD.GT.0)GO TO 60
01350         WRITE(6,70)
01360     70 FORMAT(2X,'TO CHANGE WS,COEFEY,COEFT,TEMPS,RKS, ENTER 1; IF NOT
01370        *ENTER 0')
01380         READ(5,*)NEWPAR
01390         IF(NEWPAR.GT.0)GO TO 22
01400         WRITE(6,74)
01410     74 FORMAT(2X,'TO CHANGE ALL PARAMETERS, ENTER 1; OTHERWISE ENTER 0')
01420         READ(5,*) NEWALL
01430         IF(NEWALL.GT.0) GO TO 20
01440         IF(NEWALL.LE.0) STOP
01450         END
READY
```

B.4 SAMPLE INPUT AND OUTPUT

INPUT

```
ENTER TITLE OF STUDY
* * *  TRC STUDY IN BOYNE R. BELOW ALLISTON STP  * * *
  ENTER VALUES OF NTR & NY
?
2 6
 ENTER VALUES OF Y & BST,* NTR PAIRS
?
21 0.04 61 10.7
  ENTER: UKS,XHALF,PLN,BS,HS,US,BEX,HEX,UEX
?
.02 59.4 .43 9.97 .366 .227 .1 .5 .4
  ENTER: WS,COEFEY,COEFT,TEMPS,RKS
?
1.2 .02 1.02 21.5 .0044

IF YOU WANT ONE-THIRD WIDTH VALUES ONLY ENTER NOPTN=77;OTHERWISE ENTER 0

  ENTER VALUES OF UKUR,TMP,CSPNT,USTP,NOPTN
?
.02 21.5 1172 .0296 0
```

OUTPUT

```
**********************************************************
* * * DISPERSION AND DECAY MODEL: NONCONSERVATIVE MATERIAL * * *
**********************************************************

RUN #: 1    EY=  0.0017  CSDF=  465.5  WS= 1.2  TEMPR= 21.50
U=    0.02    P=    9.97    H=    0.27    U=    0.22

 TRANSECT:  1   X=    21.0  CHANNEL WIDTH=    0.04  PLUME WIDTH=    0.02

  NO.      Y       CPT      PPT       CDF      PDF

    1      0.0   540.26  1.00000    300.42  1.00000
    2      1.5    15.60  0.02887     96.37  0.32080
    3      2.9     0.01  0.00000      0.25  0.00000
    4      4.4     0.0   0.0          0.0   0.0
    5      5.9     0.0   0.0          0.0   0.0
    6      7.4     0.0   0.0          0.0   0.0
    7      8.9     0.0   0.0          0.0   0.0
 VALUES AT E/3
    2      2.9     0.01  0.00000      0.25  0.00000

 TRANSECT:  2   X=    41.0  CHANNEL WIDTH=   10.70  PLUME WIDTH=    5.41

  NO.      Y       CPT      PPT       CDF      PDF

    1      0.0   146.09  1.00000    113.57  1.00000
    2      1.8    24.55  0.16800     28.21  0.2264
    3      3.6     0.13  0.00089      0.09  0.00077
    4      5.3     0.09  0.00006      0.00  0.00000
    5      7.1     0.02  0.00001      0.0   0.0
    6      8.9     0.0   0.0          0.0   0.0
    7     10.7     0.0   0.0          0.0   0.0
 VALUES AT E/3
    2      3.6     0.13  0.00089      0.09  0.00077
```

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Prediction of chlorine residuals in streams receiving sewage effluent / Gowda, Halappa T. P.

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